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(54) An ink jet head, ink jet recording apparatus, and a control method therefor

(57) For improving stable ink droplet ejection at high speed, an ink jet recording apparatus comprises an ink jet head having one or more ink jet units each including a nozzle (11) for ejecting ink droplets; an ink chamber (5) in communication with said nozzle on the one hand and ink supply means (6, 7) on the other hand; an elastic diaphragm (8) forming at least a portion of a wall of said ink chamber; an actuator (8, 10) responsive to drive signals so as to selectively deform said diaphragm and alter the volume of said ink chamber; and abutment means (91, 15) arranged outside of said ink chamber opposing said diaphragm with a gap being formed between said diaphragm and said abutment means when the former is not deformed. The recording apparatus further comprises drive means including an ejection signal generator for applying a first drive signal to said actuator to eject an ink droplet from said nozzle; a timer responsive to said ejection signal generator for generating a timing signal at a predetermined interval after receiving the first drive signal; and a complementary signal generator responsive to said timing signal for applying a second drive signal to said actuator to displace said diaphragm into contact with said abutment means.

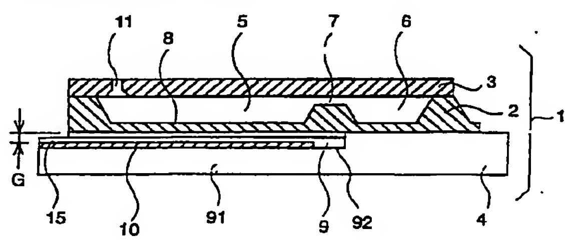


FIG. 1

EP 0 738 600 A2

Description

The present invention relates generally to ink jet printing technology, and is particularly concerned with techniques for suppressing residual ink vibration after ink droplet ejection from the ink jet head.

In general, an ink jet head has one or more ink jet units each comprising a pressure generating chamber, a nozzle in communication with the pressure generating chamber and means for applying pressure to ink to selectively eject ink droplets through the nozzle. One end of the pressure generating chamber is typically connected to an ink tank through an ink supply path, and the other end to the nozzle opening. Part of the pressure generating chamber is made to be easily deformed and functions as a diaphragm. This diaphragm is elastically displaced (deformed) by an electromechanical converter such as a piezoelectric or electrostatic actuator to selectively generate the pressure that ejects ink droplets from the nozzle.

Recording apparatuses using this type of ink jet head offer outstanding operating characteristics, including low operating noise and low power consumption, and are widely used as hard copy output devices for a variety of information processing devices. As the performance and functionality of information processing devices has improved, demand has also risen for even higher quality and speed printing of both text and graphics. This has made urgent the development of technologies enabling even finer ink droplets to be ejected consistently at even higher frequencies, i.e. a higher print speed.

Because of the structure of the ink jet head as described above, vibration remains in the ink inside the pressure generating chamber (also called the ink chamber because it is filled with ink; hereafter "ink chamber") after ink ejection, and this residual vibration can easily result in undesirably ejected ink droplets (also called "satellites"). To avoid this, the conventional approach has been to increase the flow resistance of the ink supply path connecting the ink chamber and ink tank to attenuate the residual ink vibration. However, if the flow resistance of the ink supply path is high, the ink refill supply rate to the ink chamber after ink ejection is reduced, thereby lowering the maximum ink ejection frequency, and ultimately the printing speed of the printing device.

Alternatively, as described in JP-A-56-161172/1981, residual vibration can be cancelled, and satellite emissions prevented by applying at an appropriate timing after a diaphragm drive signal a complementary signal canceling the residual vibration of the diaphragm. This resolves the problem described above, at least for applications with non-varying droplet size, and achieves a recording apparatus with a high output speed.

However, with the technology described in JP-A-56-161172/1981, the diaphragm must be driven at an appropriate timing determined by the characteristic vibration period of the ink vibration system in order to cancel the residual vibration. This is because residual vibration may actually be promoted if the cancel signal timing is inappropriate. The technology described in JP-A-56-161172/1981 therefore provides a variable resistor for adjusting the signal timing according to the characteristic vibration period of the ink vibration system. The problem here is that a sufficient vibration damping effect may not be achieved when any of the parameters determining the characteristic vibration period of the ink vibration system, e.g., the ink viscosity, changes as a result of environmental changes, such as changes of the ambient temperature.

Also, expressing various density gradations by changing the size of the ink droplets formed on a recording medium is a preferred means of improving print quality. The size of the ink droplets output by any recording apparatus, such as a printer, using an ink jet head is determined by various factors, one of which is the size (also called "ink ejection mass") of the ink droplets ejected by the ink jet head.

A technology providing plural electrostrictive means of different sizes in the ink chamber, and separately controlling and driving these electrostrictive means to eject ink droplets of various sizes, is described in JP-A-55-79171/1980. But, when this technique is applied, each of the plural, different size actuators used to deform the diaphragm must be independently driven, increasing the number of wires needed, and thus making it difficult to achieve a high nozzle density. The number of drivers also increases because of the need to separately drive each actuator, and this makes it difficult to reduce the device size.

It is an object of the present invention to provide an ink jet recording apparatus in which the residual vibration explained above is reduced and "satellites" avoided without sacrificing conventional high ink refill rates.

It is a further object of the present invention to provide such vibration dampening in an easily ascertainable and automatically adjustable manner which can eliminate user intervention requirements and user error.

It is yet another objection of the present invention to employ diaphragm vibration dampening in varying-size ink droplet applications while retaining high nozzle densities and relatively low manufacturing and component costs.

These objects are achieved with an ink jet recording apparatus as claimed in claim 1 and a method as claimed in claim 8, respectively.

Because the diaphragm contacts the abutment means (which may be an opposing wall) as a result of the second drive signal, the diaphragm is held to the abutment means with the meniscus of the ink in the ink nozzle drawn toward the inside of the ink chamber. The characteristic vibration period of the ink vibration system therefore becomes extremely short and the flow rate of the ink flow due to residual vibration increases, thereby causing a rapid decrease in ink system vibration due to viscous loss. Unwanted ink ejection due to

residual vibration in the ink system can thus be prevented, and the ink ejection cycle shortened to accomplish high quality printing at high speed.

The timer preferably outputs the timing signal at the specific timing at which the diaphragm most closely approaches the abutment means. If an electrostatic actuator is used, this makes it possible to attract the diaphragm to the abutment means by applying a relatively low voltage only. Because the speed of diaphragm displacement at this timing is slow, diaphragm behavior can be consistently controlled irrespective of any environmentally induced variation in the characteristic vibration period of the ink system (i.e., this timing need not be changed in response to , for instance, ambient temperature fluctuations).

The timer may alternatively output the timing signal at a particular time within the deflection interval during which the diaphragm is deflected from the position where the volume of the ink chamber is smallest toward the position where the diaphragm is closest to the abutment means. In this case, the diaphragm begins moving at high speed toward the opposing wall at this timing, having an effect equivalent to that when the characteristic vibration period of the ink system is shortened, and making it possible to reduce the volume of the ejected ink droplet. In other words, the volume or size of the ejected ink droplet can be varied by selecting the timing of the timing signal from plural timing points contained within said deflection interval.

When, according to an embodiment of the invention, an electrostatic actuator is used as the actuator for the diaphragm, the eject signal generator preferably comprises a charging circuit for charging the actuator, and a first discharge circuit for discharging the actuator at a first discharge rate. Moreover, the complementary signal generator comprises a charging circuit capable of charging the actuator to a charge sufficient to cause contact between the diaphragm and the abutment means, and a second discharge circuit for discharging the actuator at a second discharge rate that is slower than said first discharge rate. It is therefore possible to apply complementary charging causing the diaphragm to contact the abutment means, and then consistently restore the diaphragm to the standby position for the next ink droplet ejection operation, without unwanted ink ejection and without generating vibrations in the ink system.

Other objects and attainments together with a fuller understanding of the invention will become apparent and appreciated by referring to the following description of particular preferred and alternative embodiments and claims taken in conjunction with the accompanying drawings, in which:

Fig. 1 is a simplified longitudinal cross section, taken along line I-I in Fig. 2, of a preferred embodiment of an ink jet head according to the present invention;

Fig. 2 is a plan view of the ink jet head shown in Fig. 1;

Fig. 3A-3C are simplified lateral cross sections, taken along line III-III in Fig. 2, with Fig. 3A showing the standby state, Fig. 3B showing when ink is supplied, and Fig. 3C showing the state when the ink is compressed or pressurized;

Fig. 4 is a graph showing the relationship between the force acting on the diaphragm and the distance between the diaphragm and the opposing electrode segment;

Fig. 5 is used to describe an alternative embodiment of the diaphragm of the ink jet head;

Fig. 6 is a circuit diagram of one example of a drive circuit used in connection with the ink jet head shown in Fig. 1;

Figs. 7A-7D is a signal timing chart used to describe the operation of the drive circuit shown in Fig. 6;

Fig. 8 is a signal waveform diagram showing an example of the drive signals used to drive the ink jet head shown in Fig. 1;

Fig. 9A-9D are partial lateral cross sections of the ink jet head shown in Fig. 1, wherein Fig. 9A shows the state before ink droplet ejection, Fig. 9B shows the state when an ejection drive voltage is applied to attract the diaphragm to the opposing wall surface, Fig. 9C shows the state when the ejection drive voltage is released and the diaphragm returns toward the ink chamber, and Fig. 9D shows the state when the complementary charging voltage is applied to again attract the diaphragm to the opposing wall surface;

Fig. 10 is a simplified lateral cross section, corresponding to that of Fig. 1, of an ink jet head according to an alternative embodiment of the present invention;

Fig. 11 is a simplified lateral cross section, corresponding to that of Fig. 1, of an ink jet head according to a further alternative embodiment of the present invention;

Fig. 12 is a plan view of an ink jet head shown in Fig. 11; and

Fig. 13 is an alternate signal waveform showing an alternative example of the drive signals suited for driving the ink jet head according to the presently preferred and alternative embodiments of the present invention.

Throughout the drawings like reference symbols refer to like parts.

Fig. 1 is a cross-sectional view of an ink jet head according to the present invention, Fig. 2 is a partial plan view of Fig. 1, and Figs. 3A-3C are partial cross-sectional views of Fig. 2.

As shown in these figures, ink jet head 1 is a three-layer lamination which includes a nozzle plate 3 comprising, for example, silicon, a glass substrate 4 comprising, for example, borosilicate having a thermal expansion coefficient close to that of silicon, and a center substrate 2 comprising, for example, silicon. Plural independent ink chambers 5, a common ink chamber 6, and ink supply paths 7 connecting common ink chamber 6 to each of the ink chambers 5, are formed in the center substrate 2 by, for example, etching channels corresponding to each of these components in the surface of center substrate 2 (i.e., the top surface as seen in Fig. 1). After etching, nozzle plate 3 is bonded to the surface of center substrate 2 to complete the formation of the various ink chambers and ink supply paths.

Ink nozzles 11 each opening into a corresponding one of ink chambers 5 are formed in nozzle plate 3 at positions corresponding to one end of each ink chamber 5. As shown in Fig. 2, ink supply port 12 opening into common ink chamber 6 is also formed in nozzle plate 3. Ink is supplied from an external ink tank (not shown in the figures) through ink supply port 12 to common ink chamber 6. The ink stored in common ink chamber 6 then passes through ink supply paths 7, and is supplied to each of the ink chambers 5.

Ink chambers 5 are provided with a thin bottom wall or bottom wall portion which forms a diaphragm 8 elastically displaceable (deflectable) in the vertical direction as seen in Fig. 1. Shallow recesses 9 are formed by, e.g. etching, in the top side of glass substrate 4 at positions corresponding to each of the ink chambers 5 in center substrate 2. As a result, the diaphragm 8 of each ink chamber 5 faces recess surface 92 with a narrow gap G therebetween. In actual products the gap length may in the range of about 0.2 to 1 μm, the actual value being preferably determined based on the possible precision of manufacturing technology and the other dimensional parameters including the thickness of the diaphragm so as to obtain the desired function with little drive energy being required. Because recesses 9 of glass substrate 4 are disposed opposite diaphragms 8 of ink chambers 5, recesses 9 are referred to as the diaphragm-opposing wall, or simply opposing wall 91 (Fig. 3A-3C) forming abutment means for the diaphragm.

The diaphragm 8 of each ink chamber 5 functions in this embodiment as an electrode. An electrode segment 10 is formed on each recess surface 92. The surface of each electrode segment 10 is covered by insulation layer 15 comprising, for example, glass, and having a thickness G0 as shown in Figs. 3A-3C. As a result, each electrode segment 10 and the opposing diaphragm 8 of the respective ink chamber form a capacitor having insulation layer 15 in between its electrodes and having an electrode gap of G. With one (electrode segment 10) of the electrodes of the capacitor being rigid and the other (diaphragm 8) being flexible, this structure can be used as pressure generating means in the form of an electrostatic actuator.

A drive circuit 21 (shown in Fig. 2) is provided for driving the ink jet head by operating the electrostatic actuators (charging and discharging the capacitors) according to a print signal applied from an external source, such as a host computer, not shown in the figures. One output of drive circuit 21 is connected directly to each electrode segment 10, and the other output is connected to common electrode terminal 22 formed on center substrate 2. Drive circuit 21 will be described in detail later.

If silicon is used for center substrate 2 it may be doped with impurities to become conductive and capable of supplying charge from common electrode terminal 22 to diaphragms 8. Note that for obtaining a low electrical resistance it is also possible to form a thin-film of gold or other conductive material by vapor deposition, sputtering or other process on one surface of a silicon substrate. Center substrate 2 and glass substrate 4 are bonded by anodic bonding in this embodiment. A conductive film is therefore formed on the surface of center substrate 2 in which the ink supply paths are formed.

Cross-sectional views taken along line III-III in Fig. 2 are shown in Figs. 3A-3C. When a drive voltage is applied from drive circuit 21 to a capacitor formed by the opposing electrodes as mentioned above, a Coulomb force in the form of an attraction force is generated resulting in diaphragm 8 being deflected toward electrode segment 10, thereby increasing the volume of ink chamber 5, as shown in Fig. 3B. When the charge stored in the capacitor is then rapidly discharged by drive circuit 21, diaphragm 8 returns to its original position due to its resiliency or restoring force, thus rapidly reducing the volume of ink chamber 5, as shown in Fig. 3C and increasing the pressure therein. The increased pressure forces part of the ink contained in ink chamber 5 to be ejected as an ink droplet from the nozzle 11 associated with that ink chamber.

The relationship between the voltage applied to the opposing electrodes forming a capacitor and the behavior of diaphragm 8 is described next with reference to Fig. 4. Fig. 4 is a graph showing the relationship between the force acting on diaphragm 8 and the distance between the opposing electrodes 10 and 8 when diaphragm 8 is displaced.

The restoring force of diaphragm 8 is shown by the straight line in Fig. 4. Note that the restoring force of diaphragm 8 increases in a linear fashion proportionally to

the displacement as diaphragm 8 is deflected from the position of gap length G toward the electrode segment. The absolute value of the slope of the restoring force line expresses the reciprocal of the compliance of diaphragm 8; thus, as compliance increases, the slope decreases. The curved lines in Fig. 4 indicate the Coulomb force acting on the diaphragm 8; the Coulomb force is inversely proportional to the square of the electrode gap if the applied voltage is assumed constant. Because the Coulomb force is also proportional to the square of the applied voltage, curve (a) shifts in the direction of arrow A as the applied voltage increases, and shifts in the direction of arrow B as it decreases.

G0 in Fig. 4 is the thickness of insulation layer 15 shown in Figs. 3A-3C and represents the minimum distance between the electrodes. The position in which the diaphragm contacts the insulation layer 15 will be referred to below as the "contact position" or the position in which the diaphragm 8 contacts the opposing wall 91 (note that insulation layer 15 is fixed relative to the "opposing wall" 91 which is the member of substrate 4 below recess 9). Values d1 and d2 indicate positions where the restoring force of diaphragm 8 and the Coulomb force acting on it are balanced, d1 being an unstable balance point and d2 being a stable balance point. More specifically, when a certain voltage is applied, diaphragm 8 is deflected from G to d2 and then stops. If due to an external force diaphragm 8 is then deflected to a position between d2 and d1, diaphragm 8 will simply return to d2 again when that external force is released. However, if diaphragm 8 is displaced by an external force beyond d1 to a point near the electrode segment, since the Coulomb force is greater than the restoring force, diaphragm 8 will be deflected to the contact position, i.e., to G0, and this contact position will be retained even after the external force is released.

A high voltage shown in Fig. 4 as curve (b) is applied to the opposing electrodes to force diaphragm 8 to contact the opposing wall. When this voltage is applied, there are no balance points d1 and d2, and diaphragm 8 is immediately displaced to the contact position G0. It is to be noted that displacement of diaphragm 8 can be forced to overshoot d1 by suddenly re-applying a voltage after applying a voltage lower than this high voltage if the distance between d1 and d2 is sufficiently small. It is therefore also possible to force diaphragm 8 to the contact position using a lower voltage.

To return diaphragm 8 to the original position, the capacitor of the electrostatic actuator is fully or partially discharged as shown in Fig. 4, curve (c). This causes diaphragm 8 to begin moving toward the stable balance point d2 at a rate of acceleration determined by the difference between the diaphragm restoring force and the Coulomb force. As a result, if the applied voltage drops with sufficient speed, the restoring acceleration of diaphragm 8 will be sufficient to propel the ink droplets. Likewise, if the applied voltage is lowered gradually, the restoring acceleration of diaphragm 8 can be kept low enough to prevent ejection of any ink droplets.

Because a volume change in the ink chamber is effected by deforming the diaphragm, the term "compliance" is used here also to denote the amount of volume change of the ink chamber resulting from unit pressure acting on the diaphragm 8.

Note that in order to narrow the nozzle pitch, diaphragm 8 is designed with the smallest possible dimension in the direction in which the nozzles are arrayed, i.e., in the up and down direction as seen in Fig. 2 (the diaphragm "width" hereafter), and a large dimension in the direction perpendicular to the width (hereafter, the diaphragm "length"), e.g., a 3 mm length for a 200 micrometer width in this example. As a result, the rigidity across the width of diaphragm 8, except at the ends in the lengthwise direction of diaphragm 8, determines the amount of deformation in diaphragm 8 when an equally distributed load (pressure or Coulomb force) acts on diaphragm 8 as shown in Fig. 5. The following relationship can therefore be defined between the shape and compliance (Cm) of diaphragm 8:

$$Cm = K * L * (W^5/T^3)$$

where K is a constant, and L, W, and T are the length, width, and thickness, respectively, of diaphragm 8. As this equation shows, the compliance (Cm) of diaphragm 8 is proportional to the length (L), proportional to the fifth power of the width, and inversely proportional to the cube of the thickness (T), of diaphragm 8.

It will also be obvious that the compliance of diaphragm 8, when diaphragm 8 is in contact with the opposing wall, can be considered equal to zero. This is because even if only a third of the width in the center of diaphragm 8 contacts the opposing wall, the compliance will be less than $1/100^{th}$ because compliance is proportional to the fifth power of the width.

The preferred and alternative embodiments of the present invention are therefore described hereinbelow against this background.

A drive circuit suitable as voltage application means 21 (shown in Fig. 2) used to apply a voltage and thus drive an ink jet head constructed as described above is described below with reference to Fig. 6, which shows a circuit diagram of the drive circuit, and Figs. 7A-7D collectively showing a timing chart of drive circuit operation.

Charge signal IN1 in Fig. 6 is used to accumulate charges on the opposing electrodes (diaphragm 8 and electrode segment 10) to displace diaphragm 8, and is input through level-shift transistor Q1 to first constant current circuit 400. First constant current circuit 400 comprises primarily transistors Q2 and Q3, and resistor R1, and charges capacitor C with a constant current value resulting in a constant charge rate $\tau 1$.

First discharge signal IN2 is used to discharge the charge stored on the opposing electrodes, and thus restore diaphragm 8 to the standby (non-displaced) state. Second constant current circuit 420 comprises primarily transistors Q4 and Q5, and resistor R2, and is

configured to discharge the charge stored in capacitor C at a constant discharge rate $\tau2$ during the period in which first discharge signal IN2 is active.

Second discharge signal IN3 is used to discharge the charge stored on the opposing electrodes to restore diaphragm 8 to the standby state. Third constant current circuit 430 is configured primarily of transistors Q10 and Q11, and resistor R3, the resistance of which is greater than that of resistance R2. Third constant current circuit 430 is used to discharge the capacitor C at a constant discharge rate $\tau3$ that is slower than the discharge rate $\tau2$ of second constant current circuit 420 during the period in which the second discharge signal IN3 is active.

The terminals of capacitor C are connected to the output terminal OUT via a buffer comprising transistors Q6, Q7, Q8, and Q9. The common electrode terminal 22 of the ink jet head is also connected to the output terminal OUT, and the output of each transistor T is connected to the respective electrode segment 10.

While charge signal IN1 is active, capacitor C is charged with a constant current level. If the transistor T corresponding to the electrode segment of the nozzle from which a droplet is to be ejected is also on at this time, the corresponding pair of opposing electrodes will be charged to the same voltage level as the capacitor C. Because the capacitor C is discharged when the discharge signal is input, the charge stored on the opposing electrodes is also discharged through the corresponding diode D.

The operation of a drive circuit thus comprised is described further below with reference to the timing chart in Fig. 7A-7D.

When charge signal IN1 (Fig. 7A) becomes active, the leading edge of the charge signal sequentially turns on transistor Q1 and transistor Q2 of first constant current circuit 400. Capacitor C is thus charged using a constant current value determined by resistance of R1.

The terminal voltage of capacitor C thus rises linearly from 0 volt with a constant slope $\tau1$ as shown in Fig. 7D during the period to time t1. This slope $\tau1$ is determined by the resistance of resistor R1, and the capacity of capacitor C. A slow charge rate can therefore be set for capacitor C and the opposing electrodes connected thereto through the buffer by increasing the resistance of resistor R1. This charge rate is determined with consideration given to, for example, the ink supply rate to the ink chamber. Ink thus flows from common ink chamber 6 into ink chamber 5 through the ink supply path because diaphragm 8 is displaced toward electrode segment 10, and ink chamber 5 expands.

When charge signal IN1 becomes inactive after time Ta has passed (at time t1), transistors Q1 and Q2 turn off and charging of capacitor C thus stops. The voltage across the opposing electrodes is thus held at V0 at time t1, and diaphragm 8 stops while abutting against the opposing wall 91 (actually against insulation layer 15).

When a predetermined period Th then has passed, first discharge signal IN2 (for ink droplet ejection) becomes active (Fig. 7B). Transistor Q4 of second constant current circuit 420 thus discharges the capacitor C during period Tb at a rate determined by resistor R2. The voltage between the terminals of capacitor C thus drops linearly with slope $\tau2$ based on the resistance of resistor R2.

Note that the duration of period Tb is sufficient to completely discharge capacitor C for a given R2. When first discharge signal IN2 for ink ejection becomes inactive, transistor Q4 turns off, discharging by second constant current circuit 420 stops, and the terminal voltage of capacitor C, and, thus, the voltage across the opposing electrodes, is zero.

When charge signal IN1 again becomes active at time t4, capacitor C is again charged to a specified voltage V1 determined by the length of active period Tc, and voltage V1 is thereafter held for period Ti from time t5 to t6. When second discharge signal IN3 (complementary) then becomes active at time t6 following period Ti, transistor Q10 of third constant current circuit 430 turns on, thus causing capacitor C to start discharging through resistor R3.

The resistance of resistor R3 is greater than the resistance of resistor R2, causing the voltage between the terminals of capacitor C to drop linearly but at a rate $\tau3$ slower than the rate $\tau2$ mentioned above. Note that period Td during which the second discharge signal is active is set with consideration being given to the ink ejection frequency and the time required to completely discharge the opposing electrodes.

A drive method for an ink jet head using a drive circuit as described above is described below. The control method used after the drive voltage applied to the opposing electrodes by voltage application means 21 is cancelled is described in particular.

Fig. 8 shows one example of the voltage waveform between the opposing electrodes. The opposing electrodes are charged so that the voltage across the opposing electrodes rises to a peak value V0 at time t1, and the peak value V0 is then held until time t2. The opposing electrodes are then discharged from time t2 as described below to eject ink (charging/discharging interval X1 for ink ejection).

A defined period after time t3 at which discharging is completed, complementary charging/discharging interval X2 is accomplished from time t4 to time t7. Note that peak voltage V1 of the complementary charging/discharging interval X2 is lower than peak voltage V0. The discharge slope S2 during the discharge interval of complementary charging/discharging period X2 (the period from time t6 to t7) is set to be sufficiently lower (a slower discharge rate) than the slope S1 (the slope of the period from time t2 to t3) of the discharge period of charging/discharging interval X1 (see Figs. 7A-7D).

Charging and discharging are thus executed twice during the ink droplet ejection operation. The state

immediately before charging is shown in Fig. 9A. Note that ink surface 31 (i.e., the ink meniscus) is located near the nozzle opening of nozzle 11. When charging in charging/discharging period X1 starts from this state, diaphragm 8 is attracted to electrode segment 10 provided on opposing wall surface 92, and thus contacts the surface of insulation layer 15. Fig. 9B shows diaphragm 8 in contact with insulation layer 15. Displacement of diaphragm 8 to insulation layer 15 thus increases the volume of ink chamber 5, creating negative pressure in ink chamber 5 pulling ink surface 31 in toward ink chamber 5. After period X1 charging stops, ink flow into the ink chamber through ink supply path 7 caused by the negative pressure generated by the displacement of diaphragm 8 continues, and the pressure created by the ink flow inertia accumulates in the ink chamber. Discharging is started when the ink pressure has increased to a sufficient level at time t2. When the voltage between the opposing electrodes drops from peak voltage V0 to a predetermined voltage level, diaphragm 8 is released and is elastically displaced in the opposite direction, i.e., upward as seen in Fig. 9C, by the elastic restoring force of the diaphragm. The pressure increase caused by this elastic displacement adds to the pressure created by the ink flow inertia to create a rapid rise in the internal pressure of the ink chamber, overcoming the surface tension of the meniscus and causing ink droplet 32 to be ejected from nozzle 11 as shown in Fig. 9C.

A residual vibration of both diaphragm and ink remaining in the ink chamber after ink droplet ejection causes diaphragm 8 to elastically displace again toward the opposing wall and then away from the opposing wall causing undesirable ink droplet ejection.

In one embodiment, the method of the present invention, however, starts complementary charging period X2 to forcibly attenuate vibrations at the point at which diaphragm 8 comes closest to the opposing wall. The peak voltage V1 used at this time is lower than the peak voltage V0 used during ink droplet ejection, but results in a strong force of attraction because the charge is applied when diaphragm 8 is in contact with or nearly in contact with the opposing wall, i.e. the gap between the opposing electrodes is small. Diaphragm 8 is thus again held temporarily in contact with surface 92 (Fig. 9D). The displacement speed of the diaphragm at approximately the time when peak voltage V1 is applied is near zero, and there is therefore little change in the distance to the opposing wall even if the timing t4 at which complementary charging starts is offset slightly from the point at which the diaphragm approaches closest to the opposing wall due to, for example, temperature changes affecting the characteristic vibration period of the ink system.

After diaphragm 8 is elastically displaced to eject ink droplets, the control method of the invention as thus described forcibly constrains diaphragm displacement when the diaphragm has displaced to the position of greatest ink chamber volume, and thereby prevents unwanted vibration. The compliance of the diaphragm thus drops rapidly, and the characteristic vibration period of the ink system is extremely short. The ink flow rate inside the ink chamber and the ink supply path therefore rises, accelerating consumption of residual vibration energy. The result is a rapid drop in residual vibration in the ink system.

It is to be noted that the peak pressure inside the ink chamber resulting from residual vibration of the ink system rises rapidly, but does not rise sufficiently to cause ink ejection. This is because the diaphragm stops in contact with the opposing wall, i.e., where the ink chamber volume is greatest, and the ink surface inside the nozzle is pulled closest in toward the ink chamber.

If the capacitor formed by the opposing electrodes is rapidly discharged from this state, diaphragm 8 will return from the opposing wall surface 92 as during ink ejection, and will therefore move inside the ink chamber. Such elastic displacement of diaphragm 8 can, therefore, create a rapid increase in the internal ink chamber pressure, potentially resulting in undesirable ejection of ink droplets from nozzle 11.

The method of the present invention prevents this by gradually discharging the complementary charge of complementary charging/discharging period S2, preventing diaphragm 8 from accelerating to a velocity sufficient to cause ink droplet ejection. There is, therefore, no ejecting of unwanted ink droplets, and undesired ink system vibrations resulting from ink droplet ejection are also reduced. Complementary charging/discharging period X2 thus results in effective attenuation of overall residual vibration.

An alternative embodiment of an ink jet head is described next with reference to Fig. 10. In ink jet head 1A shown in Fig. 10, the gap G between diaphragm 8 and opposing wall surface 92 varies stepwise in the longitudinal direction of the ink chamber. Ink jet head 1A is otherwise identical to ink jet head 1 of the first embodiment above. Identical parts are therefore identified by like reference signs, and accordingly, further description thereof is omitted herein below.

As shown in Fig. 10, the back of the diaphragm 8 is flat while opposing wall surface 92 of glass substrate 4 is formed in a stepped pattern descending in the longitudinal direction of the ink chamber 5. This stepped pattern results in plural gaps of gradually increasing size between glass surface 92 and diaphragm 8. The smallest gap G1 is formed at the end of ink chamber 5 nearest to ink supply path 7, i.e., between the diaphragm and the first step of opposing wall surface 92. Adjacent to gap G1 in the middle of diaphragm 8 is formed a second gap G2 greater than gap G1. The third gap G3 formed closest to nozzle 11 is the greatest gap between opposing wall surface 92 and diaphragm 8. Each of these gaps, more accurately, the electrical gaps defined by the distance from the top surface of electrode segment 10 to the bottom of diaphragm 8 corresponds to the gap G as shown in Fig. 3A-3C.

By thus varying this gap G, the gradual drop in the voltage between the opposing electrodes during the discharge interval of the complementary charging/discharging period S2 following charging/discharging period S1 for ink droplet ejection (Fig. 8) causes the corresponding parts of diaphragm 8 to separate successively from opposing wall surface 92. More specifically, diaphragm 8 separates partially and sequentially from surface 92 starting from the part where the gap is greatest (G3), and proceeding to the part where the gap is smallest (G1). Because diaphragm 8 is released from surface 92 in parts and not all at once, undesired ink droplet ejection and ink vibration can be reliably suppressed even more, and residual vibration after ink droplet ejection can be rapidly and consistently damped.

When the rigidity of diaphragm 8 is varied stepwisely or continuously in the longitudinal direction of the ink chamber 5, the same effect as described above can be obtained, i.e., diaphragm 8 contacting opposing wall surface 92 can be consistently returned to the standby state without causing ink droplets to be ejected.

An ink jet head of this construction is described below with reference to Fig. 11. In this ink jet head 1B, the part of diaphragm 8 on the side nearest nozzle 11 at the end of the ink chamber is a thin, plate-like, low rigidity member 8a. Different from what is actually shown in Fig. 11, low rigidity member 8a need not be formed with an obvious demarcation between the thickness of low rigidity member 8a and the other parts of diaphragm 8; instead, diaphragm 8 may be formed with the thickness thereof continuously decreasing in the lengthwise direction of the ink chamber.

A further embodiment of an ink jet head in which the diaphragm 8 has different portions with different rigidities is shown in Fig. 12. In this ink jet head 1C, the base end (near ink supply path 7) of the ink chamber is wider than the rest of the ink chamber. The width of diaphragm 8 is also increased in the corresponding area to form low rigidity member 8c. As with the diaphragm thickness above, low rigidity member 8c need not be formed with an obvious demarcation between the width of low rigidity member 8c and the other parts of diaphragm 8; instead, diaphragm 8 may be formed with the width thereof continuously decreasing lengthwise of the ink chamber.

With these alternative configurations, when the opposing electrodes are gradually discharged, the diaphragm separates from the opposing wall starting from the relatively high rigidity part thereof and proceeding to the low rigidity part. The entire diaphragm is therefore not restored at the same time, and the effects obtained by gradually discharging the opposing electrodes as described above can be obtained with even greater reliability.

An alternative printing apparatus drive method according to the present invention is described below. Fig. 13 shows an alternative voltage wave applied to the opposing electrodes and particularly appropriate for driving ink jet head 1 shown in Fig. 1. Charging/discharging occurs twice in this embodiment: charging/discharging from V30 to V32 for ink droplet ejection, and charging/discharging from V33 to V35 for controlling the ink droplet eject volume. Thus, complementary charging/discharging from V33 to V35 occurs after charging/discharging from V30 to V32 for ink droplet ejection.

The opposing electrodes are first charged to peak voltage V0, attracting diaphragm 8 to contact opposing wall 91. When this charge is then discharged, i.e., after time t2 in Fig. 13, diaphragm 8 is returned toward the original non-charged standby position by the elastic restoring force thereof, and is displaced beyond the standby position into ink chamber 5. This rapidly pressurizes the ink in ink chamber 5, causing an ink droplet to be ejected from nozzle 11.

Complementary charge V33 is then applied when the ink droplet is being ejected from nozzle 11, i.e., at a point between ta and tc preceding ink droplet separation. The resulting Coulomb force attracts the complete diaphragm 8 toward opposing wall 91, causing great elastic displacement. This causes a sudden temporary drop in the ink pressure inside the ink chamber, and this acts to pull the ink droplet into the ink chamber. As a result, the volume of the ejected ink droplet is greatly reduced, a fine ink droplet is ejected, and a small dot is formed on the recording medium (paper). This action can be considered identical to the ink droplet ejection operation of an ink jet head wherein the compliance of diaphragm 8 is low and the characteristic vibration period of the ink system is particularly short as described above.

It is therefore possible to change the characteristic vibration period of the ink vibration system by controlling the point at which complementary charging V33 starts. It is therefore also possible to control the ejected ink volume by using the principle of determining the vibration period corresponding to the ejected ink volume well known to the art therefore also possible to control the ejected ink volume.

Starting complementary charging V33 (V33a) at the earliest point ta after discharging V32 is completed is equivalent to operating with an extremely short characteristic vibration period in the ink system. The ejected ink volume is therefore greatly reduced, and ejection of fine ink droplets can be achieved. Conversely, if complementary charging V33 (V33c) starts at the latest possible point tc, there is minimal real change in the characteristic vibration period of the ink system. The ejected ink volume is therefore relatively great, and a large droplet is formed. If complementary charging V33 (V33b) starts at some point between the earliest (ta) and latest (tc) points, the eject ink volume is between the smallest (V33a) and largest (V33c) levels. It is therefore possible to control the ejected ink volume by changing the start of complementary charging.

The charged state is then maintained for a particular period after complementary charging to rapidly attenuate residual vibrations in the ink system in the

same way as described in the first embodiment of a drive method above. Gradual discharging as shown by V35 is then applied, allowing diaphragm 8 to return to the standby state without causing undesired ink ejection or harmful ink vibrations in the ink chamber.

It is to be noted that in the embodiments above the timing at which charging and discharging start and stop, i.e., t1 to t7 and ta to tc, may be generated by a timing generator of various known designs. For example, a clock signal with a constant period may be counted by a counter for which the initial value can be set. The necessary timing signals can then be easily generated using a carry signal generated when the counter overflows. This configuration allows the timing signal to be freely adjusted by controlling the initial value set to the counter.

If a microprocessor is used to input the initial value, it is possible, for example, to change the V33 rise timing between ta and tc according to the print data. This makes it possible to easily control and vary the ink droplet ejection volume. The ink droplet ejection period is typically several hundred microseconds long, easily within the control capacity of today's microprocessors. Hard wired logic can be alternatively used, however, to achieve even higher printing speeds.

As will be appreciated, the control device for controlling the actuator(s) of an ink jet head in accordance with the present invention may be a separate part of an ink jet recording apparatus using the ink jet head or may be integrally formed with the ink jet unit(s) into an ink jet head.

While the invention has been described in conjunction with several specific embodiments, it is evident to those skilled in the art that many further alternatives, modifications and variations will be apparent in light of the foregoing description. Thus, the invention described herein is intended to embrace all such alternatives, modifications, applications and variations as may fall within the spirit and scope of the appended claims.

Claims

1. An ink jet recording apparatus comprising:

   an ink jet head having one or more ink jet units each including
   a nozzle for ejecting ink droplets;
   an ink chamber in communication with said nozzle on the one hand and ink supply means on the other hand;
   an elastic diaphragm forming at least a portion of a wall of said ink chamber;
   an actuator responsive to drive signals so as to selectively deform said diaphragm and alter the volume of said ink chamber; and
   abutment means arranged outside of said ink chamber opposing said diaphragm with a gap being formed between said diaphragm and said abutment means when the former is not deformed; and
   drive means including
   an ejection signal generator for applying a first drive signal to said actuator to eject an ink droplet from said nozzle;
   a timer responsive to said ejection signal generator for generating a timing signal at a first predetermined interval after receiving the first drive signal; and
   a complementary signal generator responsive to said timing signal for applying a second drive signal to said actuator to displace said diaphragm into contact with said abutment means and to keep this contact for a second predetermined interval.

2. The apparatus of Claim 1, wherein the predetermined interval is selected such that said timer generates the timing signal within the time period during which the diaphragm is displaced from a position in which the volume of said ink chamber is minimum to a position where said diaphragm is closest to said abutment means.

3. The apparatus of Claim 2, wherein the predetermined interval is selected such that said timer generates the timing signal when said diaphragm reaches the position closest to said abutment means.

4. The apparatus of Claim 2, wherein the predetermined interval is selected such that said timer generates the timing signal at a selected one of a plurality of discrete timing points within said time period.

5. The apparatus of any one of Claims 2 to 4, wherein
   said actuator comprises an electrostatic actuator including a first electrode attached to or integral with said diaphragm and a second electrode attached to or integral with said abutment means so as to face said first electrode;
   wherein the first drive signal comprises:

   an ejection charge signal component for causing electrostatic attraction between said first and second electrodes to displace said diaphragm towards said abutment means; and
   a subsequent ejection discharge signal component for discharging said electrostatic actuator at a first discharge rate to release said diaphragm from said attraction force; and
   wherein the second drive signal comprises:
   a stabilizing charge signal component for causing electrostatic attraction between said first and second electrodes to displace said dia-

phragm into contact with said abutment means; and

a subsequent stabilizing discharge signal component for discharging said electrostatic actuator at a second discharge rate slower than said first discharge rate.

6. The apparatus according to any one of the preceding claims, wherein said diaphragm comprises:

a first portion having a first thickness; and
a second portion having a second thickness;
said gap having a first gap length between said first portion and said abutment means and a second gap length between said second portion and said abutment means.

7. The apparatus of Claim 6, wherein said first and second diaphragm portions exhibit different rigidities.

8. The apparatus according to any one of claims 1 to 5, wherein said diaphragm comprises:

a first portion having a first area; and
a second portion having a second area different from said first area, said first and second diaphragm portions exhibiting different rigidities.

9. A method of driving an ink jet head having one or more ink jet units each including a nozzle for ejecting ink droplets, an ink chamber in communication with said nozzle on the one hand and ink supply means on the other hand, an elastic diaphragm forming at least a portion of a wall of said ink chamber, an actuator responsive to drive signals so as to selectively deform said diaphragm and alter the volume of said ink chamber, and substantially stationary abutment means arranged outside of said ink chamber opposing said diaphragm with a gap being formed between said diaphragm and said abutment means when the former is not deformed; the method comprising the steps of:

(a) applying a first drive signal to said actuator to force ejection of an ink droplet from said nozzle;
(b) waiting a predetermined interval; and
(c) subsequently applying a second drive signal to said actuator to cause the diaphragm to contact said abutment means.

10. The method of Claim 9, wherein the predetermined interval of step (b) is selected such that step (c) is performed when the diaphragm is displaced from a position in which the ink chamber volume is minimum to a position where the diaphragm is closest to said abutment means.

11. The method of claim 10, wherein said predetermined interval is selected such that step (c) is performed when the diaphragm has reached the position nearest to said abutment means.

12. The method of Claim 10 or 11, wherein
said actuator is an electrostatic actuator;
wherein step (a) comprises:

(a1) applying an ejection charge signal to the actuator to deform the diaphragm toward said abutment means; and
(a2) subsequently applying an ejection discharge signal to the actuator to discharge the actuator at a first discharge rate and to release the diaphragm so as to cause an ink droplet to be ejected; and
wherein step (c) comprises:
(c1) applying a stabilizing charge signal component to said actuator to deform the diaphragm into contact said abutment means; and
(c2) subsequently applying a stabilizing discharge signal to discharge the actuator at a second discharge rate slower than said first discharge rate.

13. An ink jet head comprising:

one or more ink jet units each including
a nozzle for ejecting ink droplets;
an ink chamber in communication with said nozzle on the one hand and ink supply means on the other hand;
an elastic diaphragm forming at least a portion of a wall of said ink chamber;
an actuator responsive to drive signals so as to selectively deform said diaphragm and alter the volume of said ink chamber; and
abutment means arranged outside of said ink chamber opposing said diaphragm with a gap being formed between said diaphragm and said abutment means when the former is not deformed; and
drive means including
an ejection signal generator for applying a first drive signal to said actuator to eject an ink droplet from said nozzle;
a timer responsive to said ejection signal generator for generating a timing signal at a first predetermined interval after receiving the first drive signal; and
a complementary signal generator responsive to said timing signal for applying a second drive signal to said actuator to displace said diaphragm into contact with said abutment means and to keep this contact for a second predetermined interval.

14. The ink jet head of Claim 13, wherein the predetermined interval is selected such that said timer generates the timing signal within the time period during which the diaphragm is displaced from a position in which the volume of said ink chamber is minimum to a position where said diaphragm is closest to said abutment means.

15. The ink jet head of Claim 14, wherein the predetermined interval is selected such that said timer generates the timing signal when said diaphragm reaches the position closest to said abutment means.

16. The ink jet head of Claim 14, wherein the predetermined interval is selected such that said timer generates the timing signal at a selected one of a plurality of discrete timing points within said time period.

17. The ink jet head of any one of Claims 14 to 16, wherein

said actuator comprises an electrostatic actuator including a first electrode attached to or integral with said diaphragm and a second electrode attached to or integral with said abutment means so as to face said first electrode;

wherein the first drive signal comprises:

an ejection charge signal component for causing electrostatic attraction between said first and second electrodes to displace said diaphragm towards said abutment means; and

a subsequent ejection discharge signal component for discharging said electrostatic actuator at a first discharge rate to release said diaphragm from said attraction force; and

wherein the second drive signal comprises:

a stabilizing charge signal component for causing electrostatic attraction between said first and second electrodes to displace said diaphragm into contact with said abutment means; and

a subsequent stabilizing discharge signal component for discharging said electrostatic actuator at a second discharge rate slower than said first discharge rate.

18. The ink jet head according to any one of claims 13 to 17, wherein said diaphragm comprises:

a first portion having a first thickness; and

a second portion having a second thickness;

said gap having a first gap length between said first portion and said abutment means and a second gap length between said second portion and said abutment means.

19. The ink jet head of Claim 18, wherein said first and second diaphragm portions exhibit different rigidities.

20. The ink jet head according to any one of claims 13 to 16, wherein said diaphragm comprises:

a first portion having a first area; and

a second portion having a second area different from said first area, said first and second diaphragm portions exhibiting different rigidities.

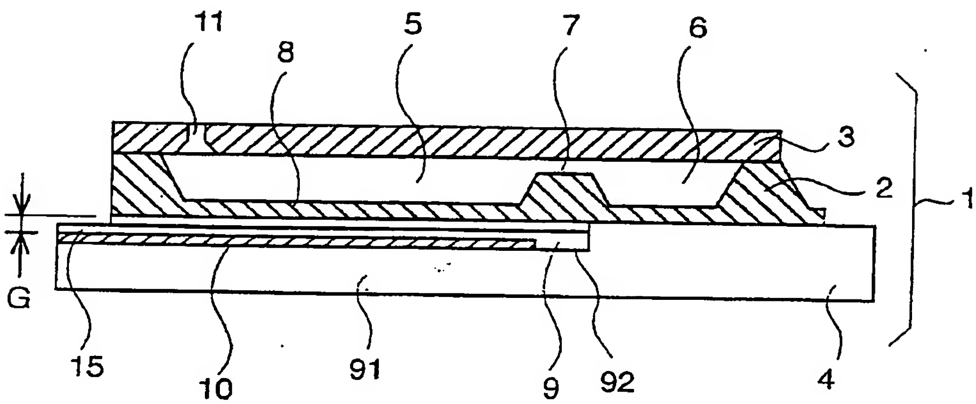


FIG. 1

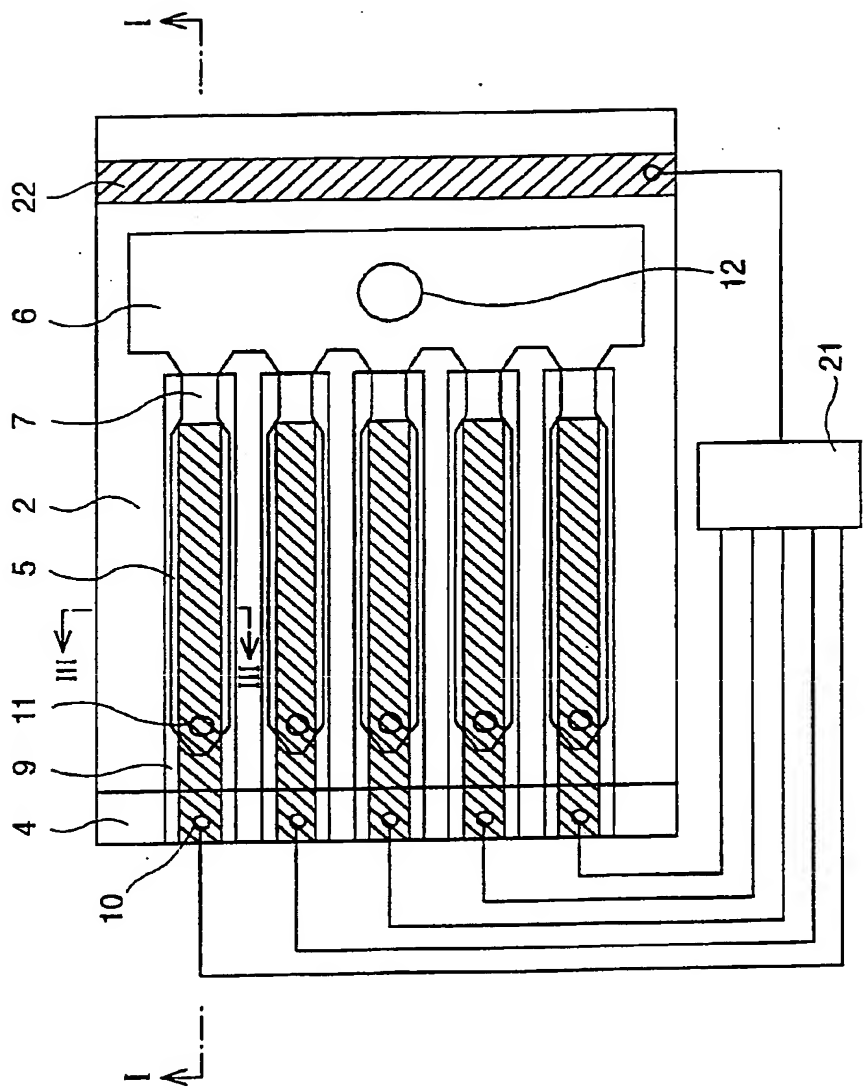


FIG. 2

FIG. 3A

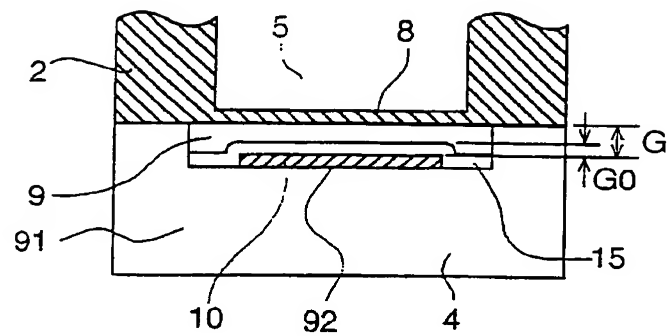


FIG. 3B

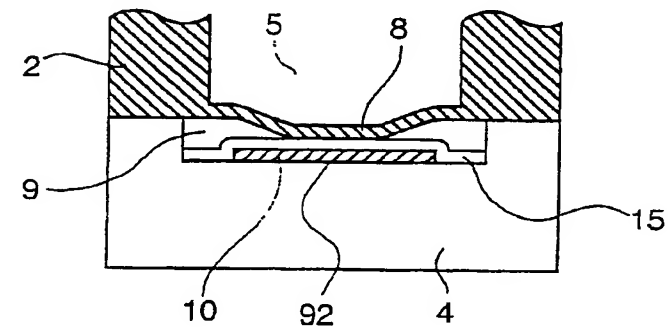
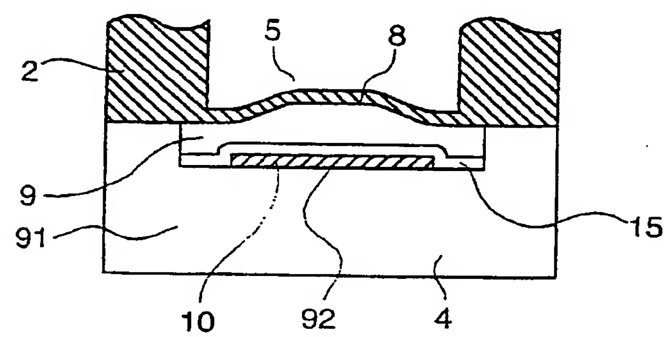


FIG. 3C



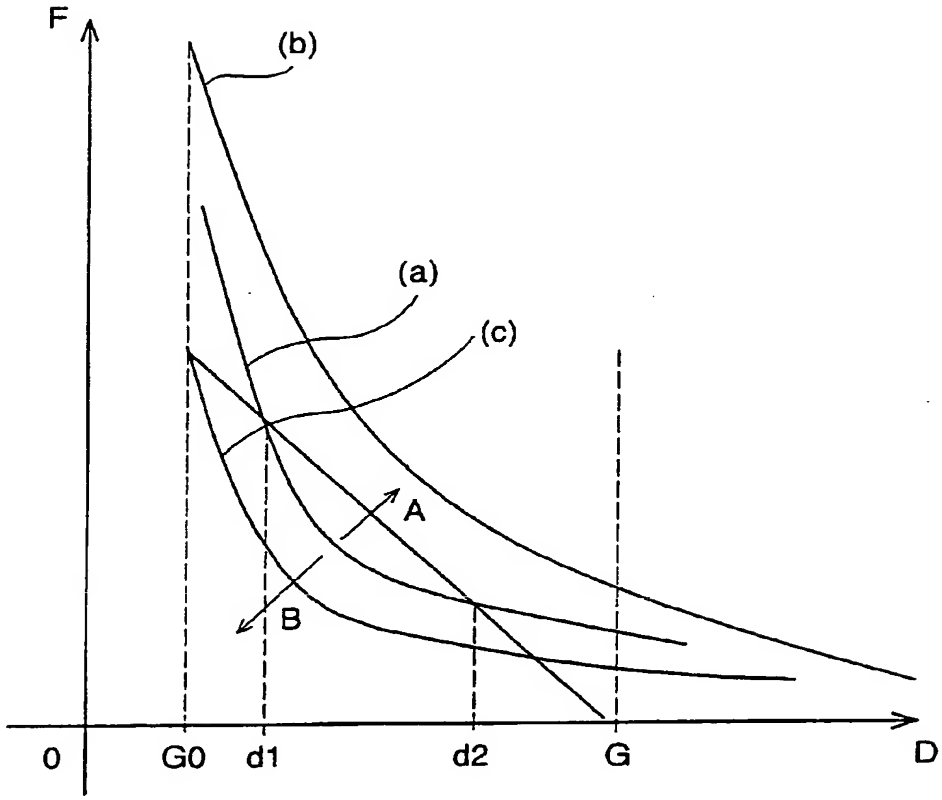


FIG. 4

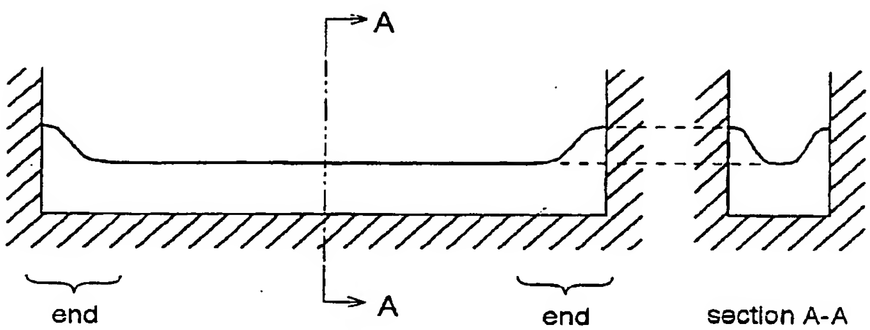


FIG. 5

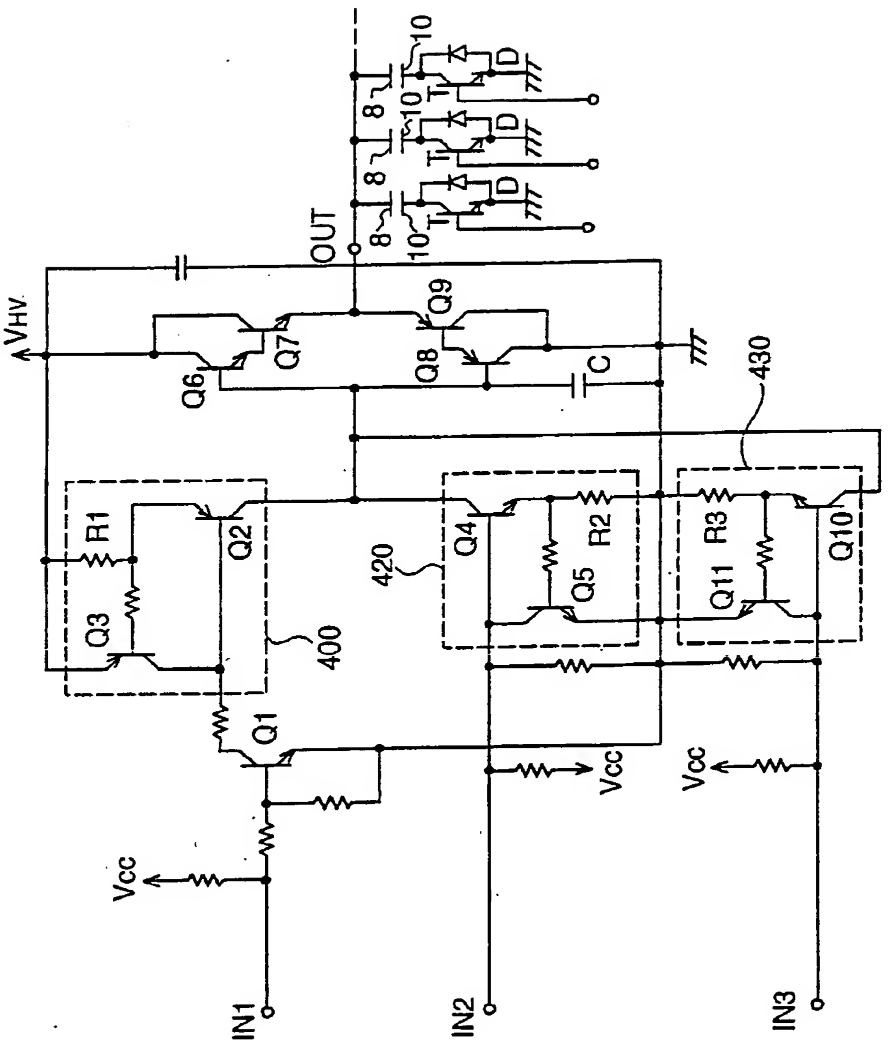

VHV
OUT
Q1
Q2
Q3
Q4
Q5
Q6
Q7
Q8
Q9
Q10
Q11
R1
R2
R3
C
D
T
8
10
400
420
430
Vcc
IN1
IN2
IN3

FIG. 6

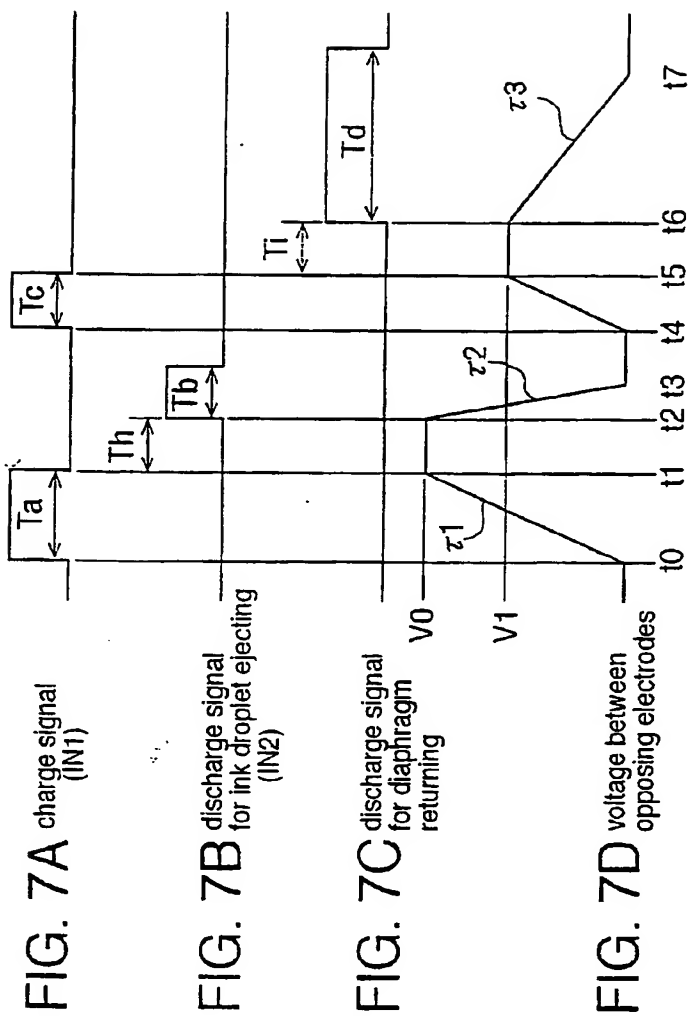


FIG. 7A charge signal (IN1)
FIG. 7B discharge signal for ink droplet ejecting (IN2)
FIG. 7C discharge signal for diaphragm returning
FIG. 7D voltage between opposing electrodes
Ta
Th
Tb
Tc
Ti
Td
V0
V1
τ1
τ2
τ3
t0
t1
t2
t3
t4
t5
t6
t7

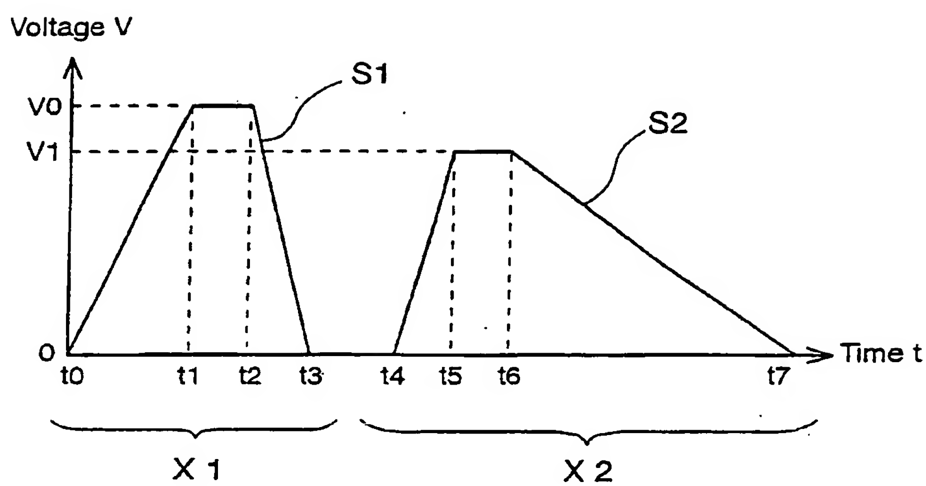


FIG. 8

FIG. 9A

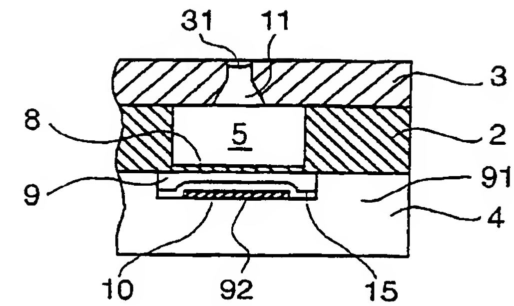


FIG. 9B

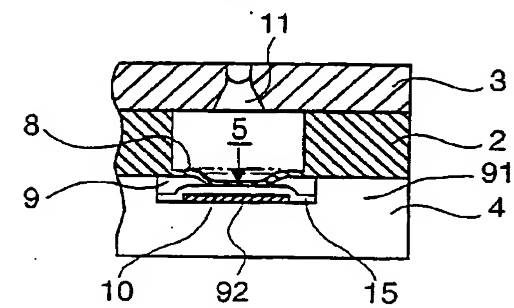


FIG. 9C

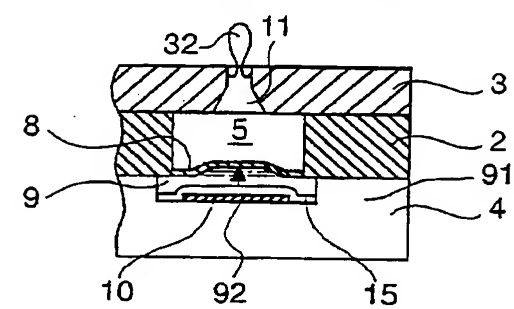
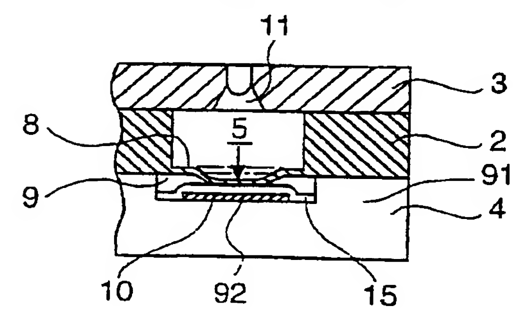


FIG. 9D



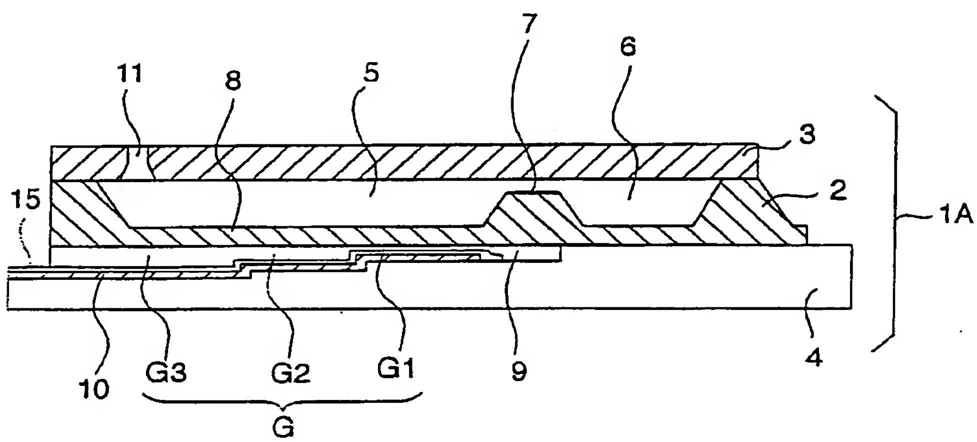


FIG. 10

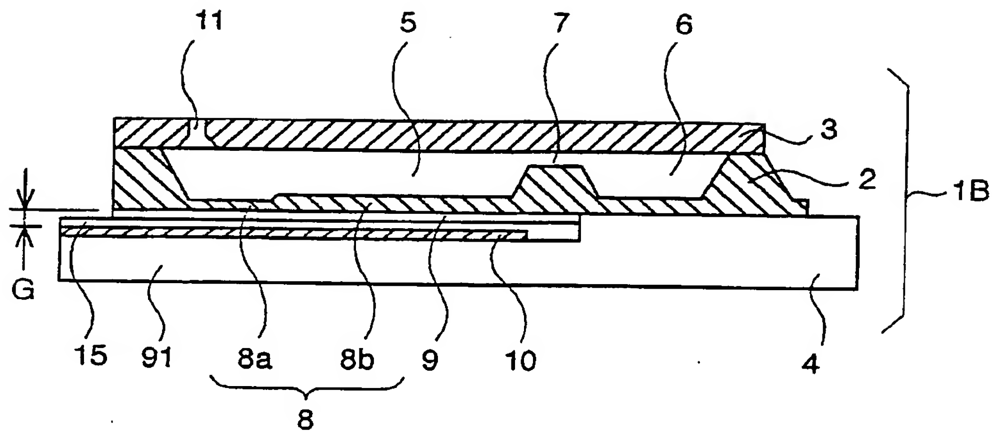


FIG. 11

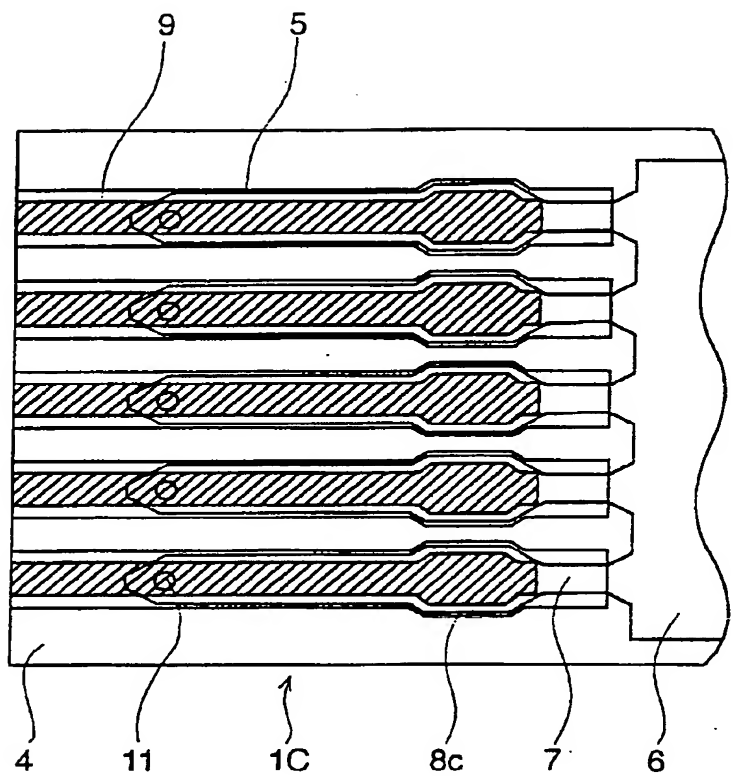


FIG. 12

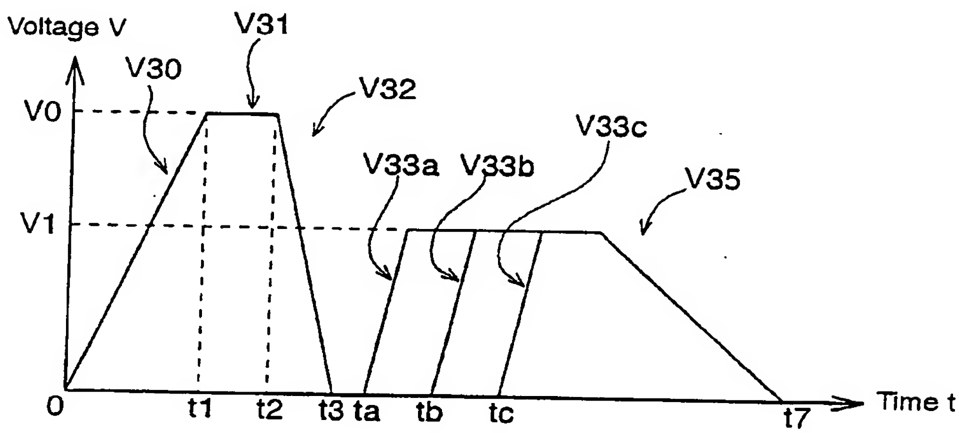

Voltage V
V31
V30
V32
V0
V33c
V33a
V33b
V35
V1
0
t1
t2
t3
ta
tb
tc
t7
Time t

FIG. 13

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